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14. ABSTRACT
In this paper we propose the design of a MEMS-deformable-mirror based optical limiter. The design is based on aperturing focused light reflected out of an optically driven deformable mirror, deformed in a parabolic form. We derived an expression for the reflected light intensity and we showed that the reflected light saturates as a function of back illumination light intensity.

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MEMS based Optical Limiter

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Abstract: In this paper we propose the design of a MEMS-deformable-mirror based optical limiter. The design is based on aperturing focused light reflected out of an optically driven deformable mirror, deformed in a parabolic form. We derived an expression for the reflected light intensity and we showed that the reflected light saturates as a function of back illumination light intensity.

Keywords: Adaptive Optics; Nonlinear optical signal processing; Optoelectronics; Optical Limiter

Introduction

Optical power limiters are important components of optical systems. As the name implies, they automatically limit the amount of optical power that is reflected or transferred through the device. For low intensities, the output beam intensity is proportional to the input beam intensity, while at higher input intensities, the output beam intensity saturates.

Many applications are in the optical signal processing area. Protection of optical sensors and detectors, against excessive input signals is an important area of application. In military applications, this may involve protection against intentional high intensity sources such as flares or laser beams directed as counter measures against the sensor system.

Very high speed limiting devices have been proposed for use in laser eye protection applications. Electro-optic materials with large third order optical nonlinearities have been proposed and utilized for optical limiting applications[1,2], but the required values of nonlinearity have been difficult to achieve, where extreme speed of response is required.

Thin films of the biomaterial bacteriorhodopsin have shown promise in optical limiting[3-5], since the effective nonlinearity is high, but the speed of response is quite slow, due to the photochemical reactions involved[6], and only moderate average power levels can be handled without damage.

Some nonlinear materials such as photorefractive crystals have been significantly used in optical pattern recognition. The ability of nonlinear saturation to enhance the correlation peak intensity and increase the signal-to-noise ratio (SNR) have been examined and successfully proved[7]. There are also some models that introduce an associative memory model to demonstrate the neural network behavior with incorporation of nonlinear threshold and feedback systems[8]. Several kinds of optical implementations of these systems using holographic associative

memories also have been introduced. This was achieved by adding a nonlinear feedback, electronically or optically[9] to the optical vector-matrix multiplier[10].

Where nanosecond or picosecond response is not a necessity, other device architectures deserve to be considered. The MEMS technology has shown considerable promise in many optical applications. Considerable design flexibility is possible, since the design parameters are not tied to the optical property of a particular optical material, and respectable speeds at the microsecond level are achievable.

In our prior work, a MEMS based all optically driven deformable mirror was designed and fabricated[11]. In this work, an optical limiter using our optically addressed deformable mirror is proposed and designed.

The architecture of this deformable mirror device, as shown in figure 1, consists of a pixellated metallized membrane mirror suspended over an optically addressed photoconductive substrate such as GaAs or InP. A grid of insulating material such as photoresist is used to support the suspended membrane and a transparent electrode (ZnO) is placed on the backside of the substrate.

A bias is applied between the metalized membrane and the transparent electrode. Illuminating the device from the back side, changes the photoconductivity across the substrate and consequently the voltage drop across the membrane and substrate, which leads to membrane deflection. The membrane deflects in a parabolic form and the deflection is proportional to the square of the applied field

Several operating mechanisms of this device have been described before[11, 12, 13]. These include: DC bias, DC bias accompanied by AC light modulation and a combination of AC and DC biases. In the DC bias operating mechanism, the device deflects in a binary fashion. In the AC light

modulation with the DC bias mode, it was possible to control the impedance only in a non steady-state situation. This suggested that this operating mechanism is suitable for moving targets or similar situations where only response to transient events is desired. In very high frequency AC light modulation, it was possible to control the impedance between the membrane and substrate under both transient and steady-state conditions, while a combination of AC and DC provided further control of the heterojunction capacitance between the transparent ZnO electrode and substrate. For the last three operating mechanisms, it was found both experimentally and theoretically that the membrane deflection saturates as a function of the back illumination intensity.

In this paper, both the saturable deflection of the membrane and the parabolic form of this deformation is utilized to create a MEMS optical limiter. It is focused in particular on using the very high frequency AC bias operating mode.

Background

According to AC bias operating mode[13], the membrane deflection is given by:

$$h = \frac{\varepsilon_0 r_1^2 q^2 \mu_n^2 (n+\Delta n)^2 A^2 V^2}{32Ts^2 \left(L^2 \omega^2 \left(\frac{\pi \varepsilon_0 r_1^2}{s} \right)^2 + q^2 \mu_n^2 (n+\Delta n)^2 A_d^{\ 2} \right)} \qquad (1)$$

And the incremental deflection from zero back illumination is

$$\Delta h = \frac{\varepsilon_0^{\ 3} r_1^{\ 6} q^2 \mu_n^{\ 2} A_d^{\ 2} V^2 L^2 \omega^2 \pi^2 (2n\Delta n + \Delta n^2)}{8T[s^2 q^2 \mu_n^{\ 2} (n+\Delta n)^2 A_d^{\ 2} + L^2 \omega^2 \pi^2 \varepsilon_0^{\ 2} r_1^{\ 4}][s^2 q^2 \mu_n^{\ 2} n^2 A_d^{\ 2} + L^2 \omega^2 \pi^2 \varepsilon_0^{\ 2} r_1^{\ 4}]} \qquad (2)$$

where ε_0 is permittivity of free space, $2r_1$ is the size of one pixel pattern, s is the depth of the well and T is the membrane tension, V is the total voltage applied across the MEMS, q is the electronic charge, μ_n is the carrier mobility, n is the carrier concentration under dark illumination

conditions, L is substrate thickness, A_d is the area of each pixel, Δn is the increase in carrier concentration due to illumination, and ω is the frequency.

At the membrane saturated point, where the term $n+\Delta n$ is maximized ($n+\Delta n \rightarrow \infty$), the deflection saturation value could be found from equation 1 as:

$$h_s = \frac{\varepsilon_0 r_1^2 V^2}{32 T s^2} \qquad (3)$$

The dimensions and parameters of one pixel of this deformable mirror are shown in Figure 2.

Theory

Figure 3 shows the proposed architecture for the optical limiter. A plane wave is incident on the membrane of a back illuminated device, the deflected membrane acts as a parabolic mirror and focuses the light up to its diffraction limit. The shortest focal length occurs at the saturated deflection. If the light at the saturation focal point is aperturized by a pinhole that has a diameter equivalent to the diffraction limit, then the light intensity that transmitted through the pinhole saturates as a function of back illumination intensity. As shown in figure 2, a lens is located at focal distance to convert the light transmitted through the pinhole to a plane wave. The output light intensity I_{out} transmitted through a circular pinhole is

$$I_{out} = \frac{\pi \delta_s^{\ 2}}{\pi (2 r_m)^2} I_{in} \qquad (4)$$

where δ_s and r_m are the beam spot sizes at saturation focal plane for focused and unfocused beam respectively. I_{in} is the plane wave intensity incident to the membrane.

Based on equation 4, we show that the transmitted light from the pinhole has a saturation dependency on the back illumination light intensity, hence:

$$I_{out} = G(y) I_{in} \qquad (5)$$

where I_{in} is the light intensity incident to the membrane and I_{out} is the reflected output light intensity from the mirror and G(y) is defined as:

$$G(y) = \left(\frac{Ay}{Ay + B} \right)^2, \tag{5.1}$$

where A and B parameters are related to the device physics and y is proportional to back illumination light intensity.

MEMS deformable membrane mirrors have parabolic deflection which allows the deformable mirror to act as a convergence mirror and thus to focus the incident beam. The diffraction limited minimum beam spot size δ at the focal point f is:

$$\delta = \frac{4}{\pi} \frac{\lambda f}{D} \tag{6}$$

Where λ is the wave length, f is the focal length and D is the aperture size which in this case is the mirror diameter ($2r_1$).

According to Equation 4, in order to derive the input-output nonlinear transfer function, it is necessary to derive the values of both δ and r_m. The r_m can be derived based on geometric consideration shown in Figure 4. This figure illustrates the light reflectance from a parabolic membrane mirror with diameter $D=2r_1$ for both saturated and non-saturated deflection modes. In the non-saturated deflection mode (outer triangle) the light is focused at the focal point f with the beam spot size of δ while for the saturation deflection mode (inner triangle) the membrane focuses the light at focal point f_s with beam spot size of δ_s.

According to this figure and considering the geometrical parameters from outer and inner triangles, the beam converging angle θ satisfies the following relationships for saturated and non-saturated deflection modes respectively:

$$\tan\theta = \frac{r_1 - \delta/2}{f} \tag{7}$$

And

$$\tan\theta = \frac{r_m - \delta/2}{f - f_s} \tag{8}$$

where $2r_m$ is the beam diameter at the saturation point and f_s is the saturated focal length (e.g. the focal length of the mirror when the mirror deflection saturates).

By equalizing equations 7 and 8 and rearranging the equation yield to

$$r_m = \left(1 - \frac{f_s}{f}\right)\left(r_1 - \frac{\delta}{2}\right) + \frac{\delta}{2} \tag{9}$$

For further evaluation of the above relationship as a function of membrane deflection h (equation 1), and hence as a function of the total incident light intensity on the back of the device, the parameters f_s and f need to be evaluated.

For that, let us assume a generic form of a parabolic mirror shape as

$$y = mx^2 + b \tag{10}$$

It is known that the focal length (f) of a parabolic mirror is proportional to the inverse of the slope (m) according to the following formula[14]:

$$f = \frac{1}{4m} \tag{11}$$

Considering the boundary conditions shown in figure 1 and assuming a parabolic deflection for the MEMS deformable mirror, it is easy to show that the membrane mirror parabolic equation is:

$$y = \frac{h}{r_1^2}x^2 + s - h \tag{12}$$

where h is the membrane deflection, s is the depth of well and $2r_1$ is the mirror diameter.

Since the slope m is known from Eq. 12, substituting it in Eq. 11 yields the focal length of the mirror at the non-saturated and saturated deflection modes respectively as follow:

$$f = \frac{1}{4m} = \frac{1}{4\frac{h}{r_1^2}} = \frac{r_1^2}{4h} \tag{13}$$

And

$$f_s = \frac{1}{4m} = \frac{1}{4\frac{h_s}{r_1^2}} = \frac{r_1^2}{4h_s} \tag{14}$$

Substituting f and f_s values in equation 9 yields

$$r_m = \left(1 - \frac{\frac{r_1^2}{4h_s}}{\frac{r_1^2}{4h}}\right)\left(r_1 - \frac{\delta}{2}\right) + \frac{\delta}{2} = \left(1 - \frac{h}{h_s}\right)\left(r_1 - \frac{\delta}{2}\right) + \frac{\delta}{2} \tag{15}$$

All the parameters in above equation are known (h from Eq. 1, h_s from Eq. 3, δ and δ_s from Eq. 6). Substituting all the terms in equation 4 yields that

$$I_{out} = \frac{A^2\left(a + b(\Delta n + n)^2\right)^2}{\left(A\left(a + b(\Delta n + n)^2\right) + B\right)^2} I_{in} \tag{16}$$

Where

$$A = 8\lambda T s^2 \tag{16 a}$$

$$B = r_1^6 V^2 L^2 \omega^2 \pi^3 \varepsilon_0^3 \tag{16 b}$$

$$a = L^2 \omega^2 \pi^2 r_1^4 \varepsilon_0^2 \tag{16 c}$$

$$b = q^2 \mu_n^2 A_d{}^2 s^2 \tag{16 d}$$

n and Δn are the substrate carrier concentration and the photo-generated carrier concentration respectively. Δn can be described as a function of light intensity I_0 incident to the back of the device which is given by:

$$\Delta n = \frac{\alpha \tau_n I_0}{h \nu A_d} \qquad (17)$$

Where α is the absorption coefficient, τ_n is the carrier's life time, h is the Plank's constant, ν is the light frequency and A_d is the illuminated area. If $y = a + b(\Delta n + n)^2$, equation 5 would be achieved.

The plot of G(y) as a function of light intensity I_0 is shown in figure 5. The plot shows the device saturation as a function of light intensity whereas the beam intensity increases, the total reflected light intensity saturates to unity.

Conclusion

This paper demonstrates the design of a MEMS-deformable-mirror optical limiter. In this design the focused light reflected out of a deformable membrane, which was deformed on a parabolic form, was aperturized via a diffraction limit pinhole. The transmitted light from the pinhole was collimated by a micro lens. An expression of the nonlinear transfer function of this device, which relates the reflected light intensity from the mirror as a function of back illumination light intensity, was derived. The theory showed the device saturation in terms of light intensity.

The architecture and its associated theory developed in this paper were confined to an integrated photoconductive based optically addressed MEMS operating with a high frequency AC bias.

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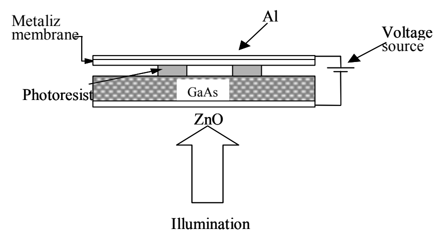

Fig. 1. MEMS deformable device

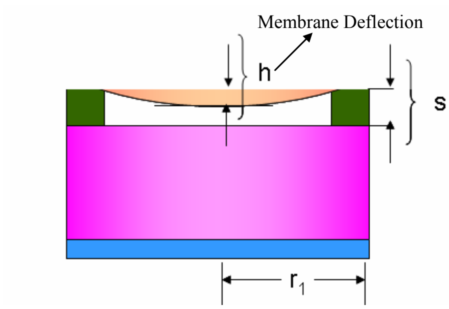

Fig 2. Deformable parabolic mirror

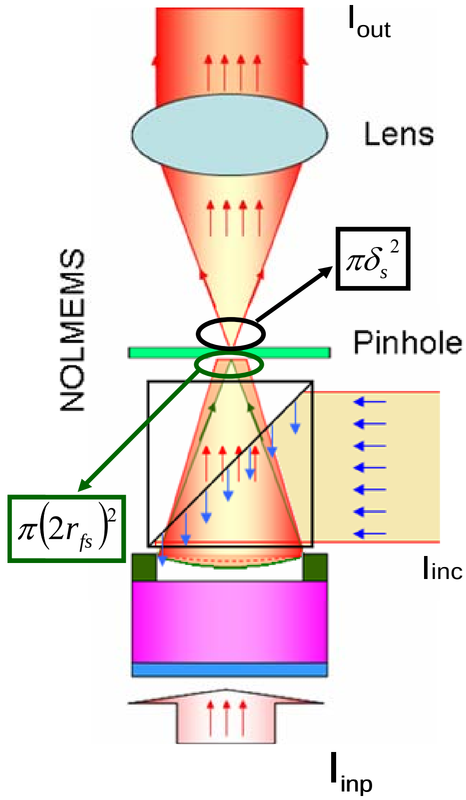

Fig 3. The proposed architecture for the MEMS based optical limiter

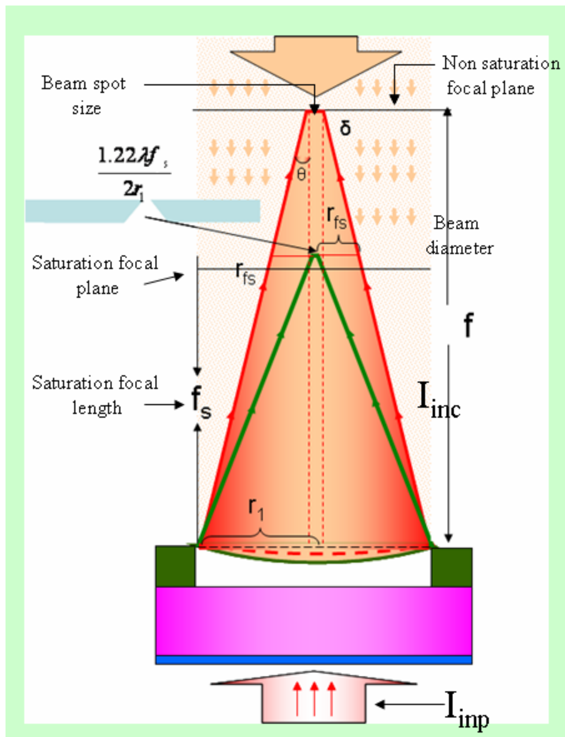

Figure 4. The light reflectance from a parabolic membrane mirror

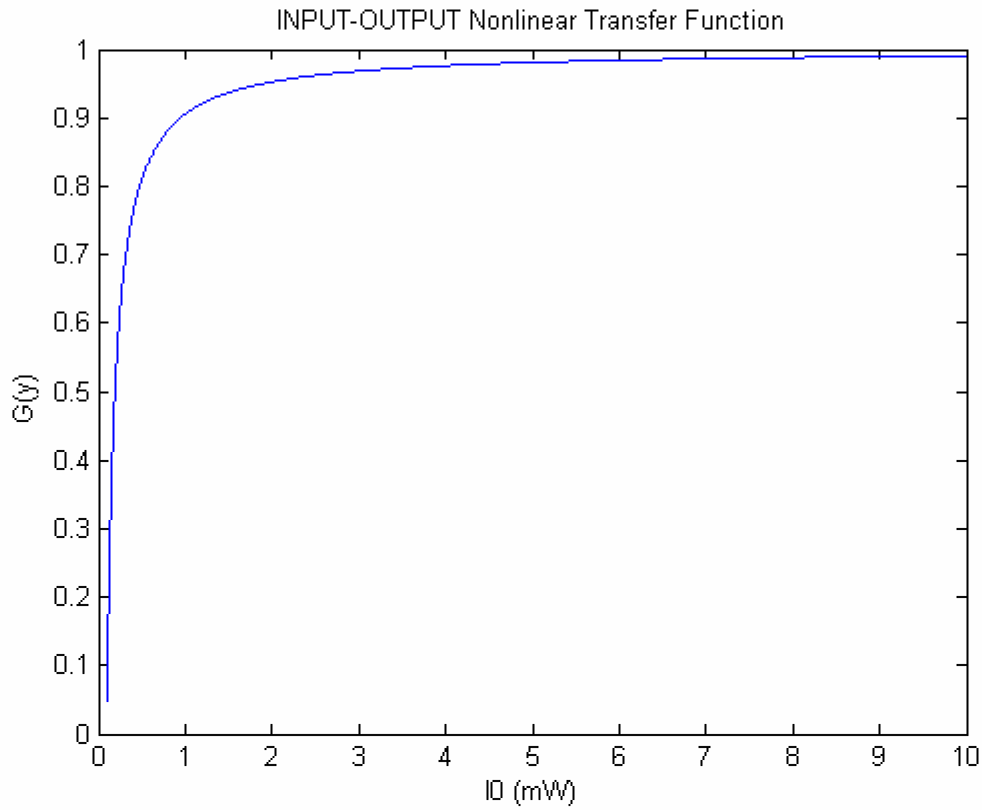

Figure 5. Input-Output Nonlinear Transfer Function of NOLMEMS